Nat. Hazards Earth Syst. Sci. Discuss., 3, 6431–6457, 2015
www.nat-hazards-earth-syst-sci-discuss.net/3/6431/2015/
doi:10.5194/nhessd-3-6431-2015
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Natural Hazards and Earth System Sciences
Discussions
Open Access

This discussion paper is/has been under review for the journal Natural Hazards and Earth System Sciences (NHESS). Please refer to the corresponding final paper in NHESS if available.

Maximum wind radius estimated by the 50 kt radius: improvement of storm surge forecasting over the Western North Pacific

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Received: 8 September 2015 – Accepted: 2 October 2015 – Published: 27 October 2015

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Published by Copernicus Publications on behalf of the European Geosciences Union.

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Abstract

Even though the maximum wind radius (R_{max}) is an important parameter in determining the intensity and size of tropical cyclones, it has been overlooked in previous storm surge studies. This research reviewed the existing estimation methods of R_{max} based on the central pressure or maximum wind speed. These over or underestimated R_{max} because of the substantial variety of the data, though an average radius could be moderately estimated. Alternatively, we proposed an R_{max} estimation method based on the radius of the 50 knot wind (R_{50}). The data obtained during the passage of strong typhoons by a meteorological station network in the Japanese archipelago enabled us to derive the following formula, $R_{\text{max}} = 0.23R_{50}$. Although this new method substantially improved the estimation of R_{max} compared to the existing models, an estimation error was unavoidable because of fundamental uncertainties regarding the typhoon's structure or insufficient number of available typhoon data. In fact, a numerical simulation from 2013 Typhoon Haiyan demonstrated a substantial difference in the storm surge height for different R_{max}. Therefore, the variability of R_{max} should be taken into account in storm surge simulations, independently of the model used, to minimize the risk of over or underestimation of storm surges. The proposed method is expected to increase the reliability of storm surge prediction and contribute to disaster risk management, particularly in the Western North Pacific, including countries such as Japan, China, Taiwan, Philippines, and Vietnam.

1 Introduction

The maximum wind radius (R_{max}) is one of the predominant parameters for the estimation of storm surges and is defined as the distance from the storm center to the region of maximum wind speed. The storm eye usually decreases in size as it deepens, with the minimum value occurring near the lowest pressure (Jordan, 1961), so that R_{max} also decreases logarithmically with the central pressure depth (Fujii, 1998).

Loder et al. (2009) examined the peak surge elevation for various physical factors for an idealized marsh and demonstrated that a difference in $R_{\max}$ of 3.7 times caused a difference of 40 % in the simulated surge height. Jelesnianski (1972) also demonstrated that surge heights tend to increase as $R_{\max}$ increases over a basin of standard bathymetry, while Jelesnianski and Taylor (1973) showed that a surge would become largest for a certain $R_{\max}$, decreasing for an $R_{\max}$ above or below the peak $R_{\max}$. However, prior to Hurricane Katrina, little attention was given to the role of the hurricane size in surge generation (Irish et al., 2008).

Several storm surges have recently occurred, causing catastrophic damage to coastal areas. Examples are the associated with Hurricane Katrina (US, 2005, approximately 2000 casualties and missing people), Cyclone Nargis (Myanmar, 2008, over 138 000 casualties), Tropical Storm Ketsana (Ondoy in the Philippines, 2009, 500 casualties), and Typhoon Haiyan (Yolanda in the Philippines, 2013, nearly 7000 casualties and missing people) (Esteban et al., 2015).

Numerical simulations have often predicted the extent of inundation due to these catastrophic storm surges. For example, in the storm surge model from the Japan Meteorological Agency (JMA), two kinds of meteorological forcing fields are used: a simple parametric model of the tropical cyclone (TC) structure and a prediction of the operational non-hydrostatic mesoscale model (JMA, 2009). Although TC forecasts with a mesoscale model have gradually improved, their mean position error remains around 100 km for 24 h forecasts (JMA, 2009). Furthermore, high spatial resolution is needed to resolve the pressure gradients near the radius of maximum winds, thus, forecasted “low-resolution” storms tend to be weaker than they can be (Persing and Montgomery, 2005). The relationship between TCs and climate can be subtle, while differences in the spatial and temporal scales are large (Elsner and Jagger, 2013). In addition, it was found that the JMA Global Spectral and Typhoon Models (GSM) underestimate the intensity of TCs in their predictions of the central pressure and maximum wind speed (Heming and Goerss, 2010). Therefore, the JMA still uses the parametric TC model

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to account for the errors in the TC track forecasts and their influence on storm surge prediction (JMA, 2009).

In a parametric model, TCs are defined by a few parameters (e.g. wind speed, central pressure, $R_{\max}$, etc.). Such reconstructions are frequently used to force storm surge and wave models or models of wind damage applied to an urban area, and are thus useful from operational forecasting and warning to climatological risk assessment and engineering design (Kepert, 2010). However, it has been commonly recognized that the results drawn from individual storms may not necessarily be representative for the majority of storms (Shea and Gray, 1973).

For hurricanes with central pressures of 909–993 hPa, in 1893–1979, the mean $R_{\max}$ was 47 km (Hsu and Yan, 1998). Fujii (1998) investigated typhoons with central pressures ≤ 980 hPa that hit the Japanese main islands and found an average $R_{\max}$ of 84–98 km, depending on the track.

However, the $R_{\max}$ should be selected depending on the characteristics of each typhoon. Therefore, several estimation models for $R_{\max}$ have been proposed. Kossin et al. (2007) correlated the $R_{\max}$ with the TC eye size (km), when a clear symmetric eye was identifiable, obtaining $R_{\max} = 2.8068 + 0.8361\,R_{\text{eye}}$, where R_{eye} is the infrared-measured eye size (km). Although this method demonstrated good accuracy, it has not yet been employed for the Western North Pacific (WNP).

Quiring et al. (2011) used the maximum wind velocity ($V_{\max}$) to estimate $R_{\max}$ for the entire Atlantic basin: $R_{\max} = 49.67 - 0.24\,V_{\max}$, with $R_{\max}$ and $V_{\max}$ in nautical miles (nmi, 1 nm = 1.85 km) and knots (kts, 1 kt = 0.52 m s^{-1}), respectively. The $V_{\max}$ is a relatively easily available parameter typically included in a TC warning. However, it must be noted that the maximum wind velocities are differently defined, depending on the oceanic basin through which the TC transits. For instance, the JMA classifies the typhoon winds based on the 10 min maximum sustained wind speed, while the United States National Weather Service (NWS) defines sustained winds using 1 min averages. These differences in classification inevitably introduce differences in the relationship between $R_{\max}$ and $V_{\max}$. Therefore Quiring et al. (2011) formula is not immediately applicable to TCs in other basins, though an empirical relationship between 1 and 10 min mean wind speeds could be applied for their conversion (Sampson et al., 1995).

The empirical formula developed by the National Institute for Land and Infrastructure Management (NILIM) (Kato, 2005) has been often used to estimate the R_{max} for storm surge simulations, particularly among Japanese coastal engineers (e.g. Takagi et al., 2012; Nakajo et al., 2014), primarily because its estimation based on the TC's central pressure (P_{c}), $R_{\mathrm{max}} = 80 - 0.769\ (950 - P_{\mathrm{c}})$ ($Pc < 950$), with R_{max} and P_{c} in km and hPa, respectively, is convenient. The Port and Airport Research Institute (PARI) and the Japan Weather Association (JWA) have also proposed exponential formulas of R_{max} (km) using the central pressure (hPa): $R_{\mathrm{max}} = 94.89\exp^{(P_{\mathrm{c}}-967)/61.5}$ (Kawai et al., 2005) and $R_{\mathrm{max}} = 52.15\exp^{(P_{\mathrm{c}}-952.7)/44.09}$ (Kitano al., 2002), respectively. An alternative R_{max} estimation based on the latitude, ψ, in addition to the pressure deficit, Δp, has been proposed by Vickery and Wadhera (2008) for TCs with a central pressure below 980 hPa traveling over the Atlantic and the Gulf of Mexico: $\mathrm{In}(R_{\mathrm{max}}) = 3.015 - 6.291 \times 10^{-5}\Delta p^2 + 0.0337\,\psi$, with R_{max}, Δp and ψ in km, hPa, and degree, respectively.

The purpose of this paper is to examine the existing models for R_{max} estimation and propose a new formula to minimize the estimation errors that result in an over or underestimation of the storm surge height. The meteorological data for the development of a reliable model for typhoon and storm surge simulation were obtained from 10 stations, from Japan's southern small islands. Our new methodology is expected to improve storm surge prediction particularly for the WNP including Japan, China, Taiwan, Philippines, and Vietnam.

2 Methodology

In this section, the data for the TC analysis, using only typhoons crossing the Japanese archipelago, is clarified. A brief description of the storm surge model is also presented.

2.1 Collection, selection, and processing of TC data

The major problems in obtaining TC maximum wind observations result from the sparseness of oceanic stations (Akinson et al., 1977). However, the good density of meteorological stations along the Japanese archipelago has a great potential for collecting data during TC passages. Figure 1 indicates the 10 meteorological stations in Japan's southern islands operated by the JMA. Using data from these stations, it was possible to analyze typhoons traveling within about 800 km between Naze and Yonagunijima (Fig. 1).

As a TC approaches the Japanese main islands, its track, shape, and intensity are altered due to topographical disturbance (Fujii, 2006). Therefore, the use of data from these remote inlands avoids the substantial changes in the TC structure induced by land topography.

The sampling of data in the selected stations was restricted to when the station experienced low pressures ($P_c < 935$ hPa) during the typhoon passage. The distance between the TC center and each meteorological station was calculated. The TCs transiting within about 100 km from one or more stations were selected, while the vast majority of the TCs that traveled far from the stations were neglected, as they seemed to be less influential.

Recent major TCs, such as 2004 Hurricane Katrina (National Hurricane Center, 2005), 2008 Cyclone Nargis (Joint Typhoon Warning Center, 2012), 2012 Hurricane Sandy (National Hurricane Center, 2012), and 2013 Typhoon Haiyan (Takagi et al., 2015a) had very low central pressures (895–940 hPa) and caused severe storm surges. Eighty percent of all hurricane damage is caused by less than 20 % of the worst events (Jagger et al., 2008). Therefore, only TCs with pressures below 935 hPa and likely to cause significant storm surges were included in our study.

Since only after 1990 the JMA meteorological information contained hourly central pressures and wind speeds (before the data were limited to 3 or 6 h intervals), only data from 1990–2013 were used.

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A TC track analysis in the WNP was carried out using the best track data from the JMA, which consisted in the time, geographical position, sea level pressure at the storm center, maximum sustained wind speed, and auxiliary information for every 3 or 6 h.

Only 17 out of the 621 TCs from 1990 to 2013 met the criteria and were used in our study. Their characteristics and tracks are presented in Table 1 and Fig. 2, respectively.

2.2 Storm surge model

The development of a new formula mainly aimed to improve the estimation of storm surges. Therefore, its effectiveness should be assessed through storm surge simulations. Takagi et al. (2015a) reproduced the storm surge from 2013 Typhoon Haiyan for various parts of the Philippines, including Leyte, Samar, and Cebu. We extended this simulation by incorporating the new $R_{\max}$ estimation, to see if the simulation reasonably estimated the observed surge heights.

We applied a parametric typhoon model based on the Myers formula (Takagi et al., 2012) coupled with the fluid dynamics model Delft3D-FLOW to estimate the extent of the storm surge in the Philippines during Typhoon Haiyan. This parametric typhoon model calculated both pressure and wind fields using the parameters from the typhoon track dataset of the JMA (i.e. central positions and pressures). The Delft3D-FLOW model was applied to the simulation of a storm surge traveling from the deep sea to shallow waters and eventually running over Tacloban's downtown. Although this model is applicable to a 3-D domain, the present study used a 2-D horizontal grid, making the code equivalent to a non-linear long wave model, the most commonly used for storm surge simulations.

The atmospheric pressure inside a TC is generally expressed by an empirical formula. For our model, the Myers formula was adopted to calculate the pressure at a distance r from the TC center $P(r)$ (Myers, 1954):

$$P(r) = P_0 + \Delta P \cdot \exp\left(-\frac{R_{\max}}{r}\right) \tag{1}$$

where r denotes the distance from the center of the typhoon, P_0, the pressure at the typhoon center, ΔP, the drop in pressure, and $R_{\max}$, the radius of the maximum wind.

For the estimation of $R_{\max}$, since the geographic locations (latitude and longitude) of the TC center from the best track were recorded every 3 or 6 h, the points were spatially converted to the Universal Transverse Mercator (UTM) coordinate system and then temporally interpolated to hourly data. Then, the distance between the TC center and each station was calculated. The pressure at the closest station was estimated by Eq. (1) for different $R_{\max}$ and compared with the observed pressure at the station. The radius that provided the best estimation was considered the optimum $R_{\max}$.

To assess which areas of the country were affected, the simulation was initially carried out for a wide area encompassing most of the Philippines. Then, a more detailed simulation was performed for San Pedro Bay in the Leyte Gulf, an area where the massive storm surge engulfed and claimed thousands of lives. The numerical simulation for these two domains had already been implemented in previous work from the authors (Takagi et al., 2015a).

3 Results and discussion

In this section, the estimations of $R_{\max}$ based on the existing models are reviewed, and subsequently a new method is proposed to overcome significant estimation errors. Furthermore, a storm surge model is performed to investigate the sensitivity of the storm surge height to changes in $R_{\max}$.

3.1 $R_{\max}$ estimation based on the central pressure

Figure 3 contains the scatter plot between the P_c and the estimated $R_{\max}$ along with the regression curves from the NILIM, PARI, and JWA models, and the linear regression line for the present 17 TCs ($R_{\max} = 0.676\,P_c - 578$, with $R_{\max}$ and P_c in km and hPa). Particularly, the PARI model described well the average $R_{\max}$. The NILIM and

JWA models slightly over or underestimated the radius, though the lines were present within the entire plots. The $R_{\max}$ derived for 11 strong cyclones with central pressures of 920–944 hPa is also indicated (Hsu and Yan, 1998) and was similar to the present regression line at around 925 hPa. The model from Vickery and Wadhera (2008), assuming a latitude of 27° N as a central value for the meteorological station distribution (Fig. 1), slightly underestimated the plots.

However, individual points greatly scattered around the regression lines. In fact, the coefficient of determination R^2, which indicates how well a statistical model fits the data, was 0.058, confirming a weak correlation.

3.2 $R_{\max}$ estimation based on the maximum wind speed

The $V_{\max}$ is negatively related to the $R_{\max}$ (Shea and Gray, 1973), suggesting that years with more intense TCs tend to have smaller than average $R_{\max}$ (Quiring et al., 2011). Figure 4, derived from the 17 studied typhoons, confirmed the same trend. However, the correlation between $V_{\max}$ and $R_{\max}$ was weak, as confirmed by the R^2 of 0.112. In addition, the fact that $R_{\max}$ is highly sensitive to slight changes in $V_{\max}$ brings more difficulties in determining the optimum $R_{\max}$. Shea and Gray (1973) confirmed that a significant variation in the relationship between these two parameters exists, particularly for lower tropospheric data, obtained through aircraft reconnaissance by the National Hurricane Research Laboratory. Therefore, the validity of the estimation of $R_{\max}$ based on $V_{\max}$ is questionable at least for the WNP.

3.3 New $R_{\max}$ estimation based on the 50 kt wind radius

The relative inadequacy of the P_c and $V_{\max}$ as predictors of the $R_{\max}$ motivated the authors to investigate another methodology to minimize the estimation error. The Regional Specialized Meteorological Center (RSMC) Tokyo led by the JMA is responsible for issuing TC track and intensity forecasts over the WNP. The JMA produces forecasts of the center position and associated 70 % probability, direction, and speed for 120 h

(Knaff, 2010), among other information (Fig. 5). We considered that the radius of the 50 kt winds around the typhoon (R_{50}) could be alternatively used for the estimation of R_{max}, since both the R_{max} and R_{50} are spatial parameters that directly represent TC sizes. The R_{50} is defined as the maximum radial extent of the winds reaching 50 kt in nautical miles.

The R_{max} proportionally increased with the increase in R_{50} (Fig. 6), according to the following average linear relationship:

$$R_{\mathrm{max}} = 0.23\ R_{50}. \tag{2}$$

For asymmetries in the R_{50}, an average value between the longest and shortest radii could be used. The R^2 was 0.57, demonstrating a relatively high correlation. The plot scatter tended to decrease with decreasing R_{50}, implying that the reliability of the R_{max} estimation would improve for stronger TCs, since they generally intensify with decreasing R_{max}.

Although this new method was expected to improve the estimation of R_{max}, an estimation error was unavoidable because of the fundamental uncertainty regarding the TC structure. Therefore, to minimize the risk of over or underestimation of storm surges, the surge simulations should be repeated for different estimation lines covering a certain percentage of the data (e.g. a 95 % prediction interval), such as $R_{\mathrm{max}} = 0.15\ R_{50}$ to $0.35\ R_{50}$.

Figure 6 also indicates the estimated R_{max} for the Atlantic from Kimball et al. (2004), after converting the wind speed from a 1 to a 10 min mean and an interpolation to match the R_{50}.

3.4 Storm surge simulation based on the new R_{max} model

The Haiyan caused the worst storm surge disaster in the recorded history of the Philippines, striking Leyte Island in November 2013 and causing inundations of up to 7 m in Tacloban City, where most casualties took place. High inundation heights were observed even outside the Leyte Gulf along the east coast of Eastern Samar, which faces the Pacific Ocean in the deep Philippine Trench. The Haiyan generated the strongest winds among over 400 past storms, being 16 % stronger than the second strongest recorded typhoon. The Haiyan forward speed nearly doubled the average speed of these weather systems, potentially making it the fastest recorded typhoon (Takagi et al., 2015b). A numerical simulation indicated inundation above 3 m along the entire bay and up to 6 m in the inner bay (Fig. 7, Takagi et al., 2015a). The maximum hindcast significant wave heights caused by the extremely strong winds reached 19 m off Eastern Samar (Bricker et al., 2014; Tajima et al., 2014; Roeber et al., 2015).

Figure 8 presents the estimated maximum storm surge heights for six locations around San Pedro Bay (Fig. 7). The simulation was implemented for two different radii covering the 95 % prediction interval, namely $R_{\mathrm{max}} = 0.15\ R_{50}$ and $0.35\ R_{50}$, to examine the sensitivity of the results to R_{max}. Except for Basey and Basiao, the observed heights were mostly within the two estimated values, implying that an estimation for different radii is effective to mitigate the estimation errors. In other words, storm surge simulations must take into account the R_{max} uncertainty rather than using a singular value, to avoid significant errors.

Although previous research (e.g. Jelesnianski, 1972; Loder et al., 2009) suggested that peak surge elevation would increase for a large R_{max}, this is not always true as the surge increased even for smaller R_{max} in some locations (Fig. 8). It is interesting to note that the simulation based on the small radius ($= 0.15\ R_{50}$) exhibited a far larger surge height than the ones based on the large radius ($= 0.35\ R_{50}$), particularly for Tanauan. In contrast, the surge increased with the typhoon radius for Airport, Anibong, and Bridge. Since Tanauan was located nearby the TC's center (Fig. 9), the storm surge height was more susceptible to R_{max} changes there than at distant locations.

3.5 Applicability and limitations of the new model

The R_{max} was significantly scattered when derived from the P_{c} or V_{max} (Figs. 3 and 4). This resulted in the development of a new approach with smaller estimation errors, where the R_{max} was estimated based on the R_{50} by Eq. (2). The relatively high R^2 demonstrated that the new method effectively reduced the estimation error of R_{max}.

As the R_{50} is easily obtained, the method can be applied to any TC transiting over an ocean basin, for which R_{50} values are available from a reliable meteorological agency. The RSMC Tokyo, a regional specialized meteorological center under the World Meteorological Organization (WMO), covers a vast area of the WNP including Japan, China, Taiwan, Philippines, and Vietnam and issues TC information (Fig. 5) and warnings to the neighboring agencies, when a typhoon arises. To mitigate typhoon-related disasters, the authorities could instantaneously predict storm surge using a simple parametric typhoon model, incorporating the R_{50} or other parameters estimated by a precise model from a neighboring meteorological agency. This method should particularly facilitate a prompt early warning by local authorities who cannot operate complex non-hydrostatic mesoscale models, but have sufficient precise local data (e.g. topography, bathymetry, infrastructure conditions, and household information) to greatly improve the prediction of the local amplification of the storm surge.

However, some estimation errors (Fig. 6) were unavoidable because of fundamental uncertainties in the TC structure and insufficient number of available TCs to derive the relationship from Eq. (2). For example, a challenge in the R_{max} estimation is associated with the occurrence of “flat” tangential wind profiles, i.e. when the wind decays very slowly with the radius (Kossin et al., 2007). These errors resulted in over or underestimations of the TCs and their subsequent storm surges, whose heights substantially varied with R_{max} changes (Fig. 8). Figure 6 also presents a remarkable discrepancy in the R_{max} estimated by the present method for the WNP and the Atlantic, meaning that our method may underestimate the R_{max} in other basins. This gap may be associated with the difference in TC sizes between different basins, as Kimball et al. (2004) suggested that the TC eyes are relatively smaller in the WNP than in the Atlantic, potentially resulting in smaller R_{max} in the former.

It should also be noted that various R_{max} have been assumed in the studies of Typhoon Haiyan. Takagi et al. (2015a) simulated the storm surge (Fig. 7) by subjectively estimating R_{max} in 15–25 km based on the empirical judgment that the heaviest rainfall in intense tropical cyclones occurs near the radius of maximum wind (Muramatsu, 1985) (Fig. 9). However, using Eq. (2), the R_{max} when the typhoon struck Leyte Island was estimated in 34 km, with an R_{50} of 80 nmi (= 148 km). Although the reason for this discrepancy is not clear, it can be partly explained by the fact that the inner radar eye radius (IRR) occurs at radii of 5–6 nmi inside the R_{max} (Shea and Gray, 1973). Mori et al. (2014) estimated the R_{max} that best described the storm in 50–60 km using numerical weather prediction and a storm surge model, while Kim (2015) assumed it as 30.2 km for the Leyte Gulf landfall for Holland's wind model (Holland, 1980). These substantial differences in radius imply fundamental difficulties in a precise estimation of R_{max}, even using the best knowledge and current technology.

The consideration of these uncertainties in storm surge simulation is also relevant regarding the uncertainty in the TC information issued by the agencies. An examination of our 17 selected TCs indicated that temporal changes in R_{max} averaged 0.75 % h^{-1} and reached up to 8.3 % h^{-1}. For the RSMC Tokyo, the wind radii estimates are part of the 3 h advisories and warnings from the JMA. Therefore, the R_{max} may change up to 24.9 % until the next information is available. These temporal changes in R_{max} are another source of error that must be considered.

Therefore, the variability of R_{max} should be taken into account in storm surge simulations, regardless of the model used, to minimize estimation errors that may compromise an early evacuation of the population.

4 Conclusions

Using observations from many Japanese islands and best track data, 17 typhoons with central pressures below 935 hPa that passed near meteorological stations were selected to examine existing and a new method to calculate R_{max}. The existing methods based on the central pressure or maximum wind speed showed substantial scattering around the regression lines. Alternatively, we proposed an R_{max} estimation based on the radius of the 50 kt wind (R_{50}). Although it was expected to substantially improve the estimation of R_{max}, an estimation error was unavoidable and resulted in an over or underestimation of storm surges. In fact, the simulations of the storm surge from 2013 Typhoon Haiyan demonstrated that the estimated storm surge heights substantially varied with changes in R_{max}, highlighting a fundamental difficulty in estimating surge heights based on only one predetermined radius. Therefore, to minimize the risk of storm surge over or underestimation, the variability of R_{max} should be taken into account in the simulations, regardless of the model used. The proposed R_{max} estimation method is expected to increase the reliability of storm surge predictions and contribute to disaster risk management of tropical cyclones and storm surges.

Acknowledgements. The present research was funded by the JSPS KAKENHI Grant Number 26702009 and the Environment Research and Technology Development Fund (S-14) of the Ministry of the Environment, Japan. The JMA typhoon best track data is available at http://www.jma.go.jp/jma/jma-eng/jma-center/rsmc-hp-pub-eg/besttrack.html, while the JMA meteorological station network data for the Japanese archipelago can be found at http://www.data.jma.go.jp/obd/stats/etrn/index.php.

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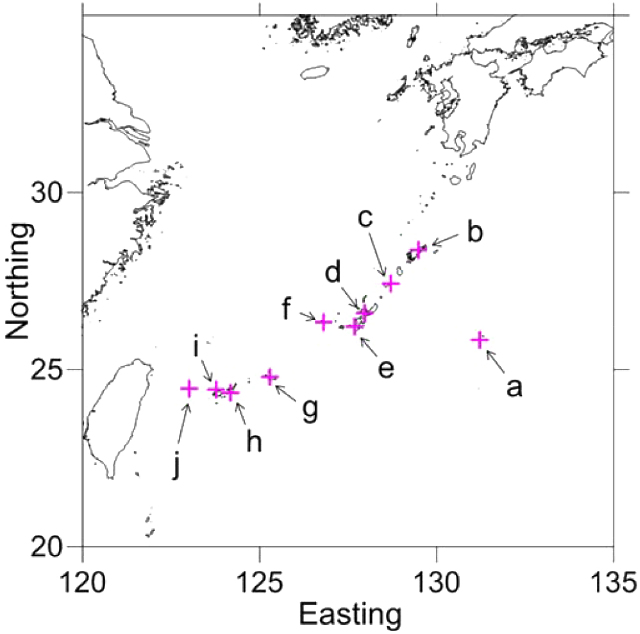
Table 1. Characteristics of the 17 typhoons selected for this study.

No.	Typhoon	Progress of the central pressure (hPa)[a]	Maximum wind velocity (kt)[b]	Nearest station[c]	Distance of TC center from nearest station (km)	Estimated R_{max} (km)
1	9019	925 → 920 → 915 → 910 → 905 → 900 → 895 → 890 → 895 → 900 → 905 → **910** → 915 → 920 → 925 → 930	102	b	51	45
2	9313	930 → **925** → 930	95	f	19	40
3	9416	925 → **930**	95	h	47	70
4	9609	930 → **925**	95	i	22	70
5	9918	**930**	90	f	39	35
6	0314	930 → 925 → 920 → 915 → **910** → 915 → 920 → 925 → 930	105	g	12	32.5
7	0418	**925** → 930	95	d	14	80
8	0608	930 → **925** → 930	103	g	63	25
9	0613	930 → 925 → **920** → 925 → 930	110	h	18	40
10	0704	**930**	95	e	23	62.5
11	0712	930 → **925** → 930	100	i	7	35
12	0715	**925** → 930	105	j	13	50
13	0815	905 → 910 → 915 → 920 → **925** → 930	100	j	88	30
14	1011	**930**	95	j	52	35
15	1215	920 → 915 → 910 → 915 → 920 → 925 → **930**	85	d	4	67.5
16	1216	920 → 925 → **930**	93	e	100	40
17	1217	920 → 925 → **930**	90	e	32	45

[a] The numbers in bold indicate the pressure of the typhoon, when it passed the station.

[b] The maximum wind velocities (V_{max}) presented are from when the typhoon passed near a station.

[c] Naze (b), Nago (d), Naha (e), Kumejima (f), Miyakojima (g), Ishigakijima (h), Iriomotejima (i), and Yonagunijima (j).



No	Station	E	N
a	Minamidaitoujima 南大東島	131.23	25.83
b	Naze 名瀬	129.50	28.38
c	Okinoerabu 沖永良部	128.71	27.43
d	Nago 名護	127.97	26.59
e	Naha 那覇	127.69	26.21
f	Kumejima 久米島	126.80	26.34
g	Miyakojima 宮古島	125.28	24.79
h	Ishigakijima 石垣島	124.16	24.34
I	Iriomotejima 西表島	123.77	24.43
j	Yonagunijima 与那国島	123.01	24.47

Figure 1. Ten meteorological stations along the Japanese archipelago operated by the Japan Meteorological Agency (JMA): Minamidaitoujima **(a)**, Naze **(b)**, Okinoerabu **(c)**, Nago **(d)**, Naha **(e)**, Kumejima **(f)**, Miyakojima **(g)**, Ishigakijima **(h)**, Iriomotejima **(i)**, and Yonagunijima **(j)**.

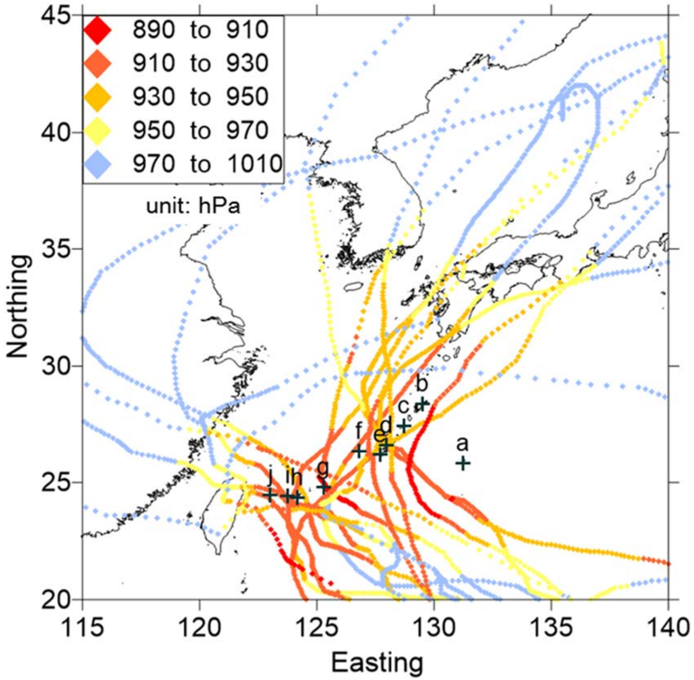


Figure 2. Tracks of the 17 selected tropical cyclones transiting over the southern Japanese ocean. The color differences represent the changes in central pressure. The crosses indicate the location of the 10 meteorological stations operated by the Japan Meteorological Agency (JMA): minamidaitoujima **(a)**, Naze **(b)**, Okinoerabu **(c)**, Nago **(d)**, Naha **(e)**, Kumejima **(f)**, Miyakojima **(g)**, Ishigakijima **(h)**, Iriomotejima **(i)**, and Yonagunijima **(j)**.

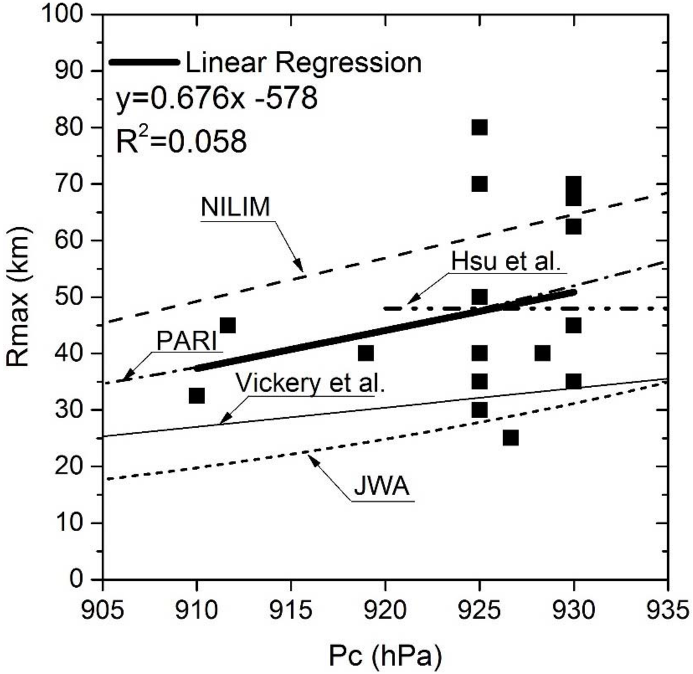


Figure 3. Wind radii and central pressures of 17 tropical cyclones and estimations from the National Institute for Land and Infrastructure Management (NILIM), Port and Airport Research Institute (PARI), Japan Weather Association (JWA), Hsu and Yan (1998) models, and Vickery and Wadhera (2008).

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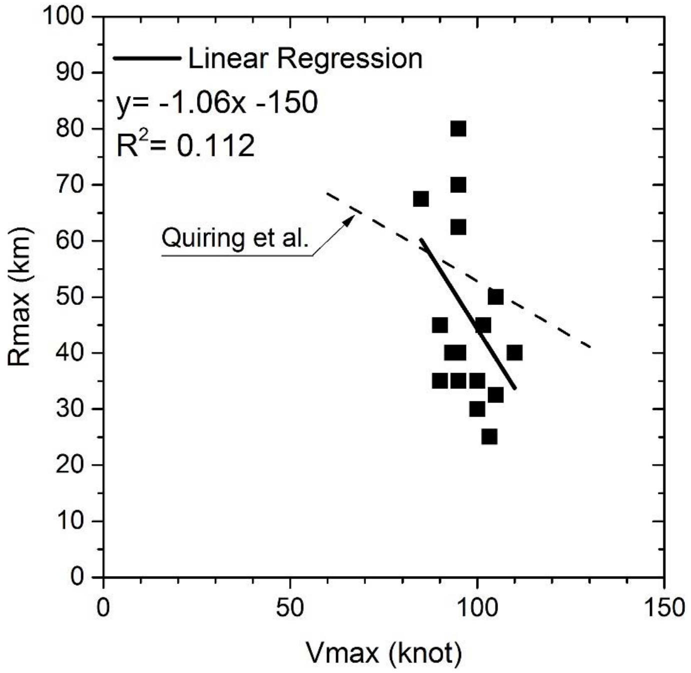
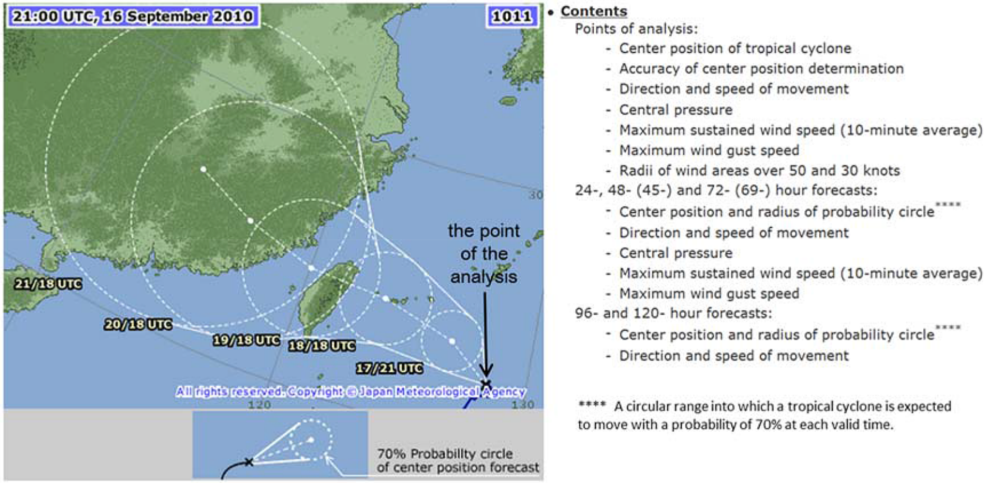


Figure 4. Estimated wind radii (R_{max}) vs. the maximum wind speeds (V_{max}) for the 17 studied tropical cyclones. The estimation by Quiring et al. (2011) is also presented after the mean wind speed conversion according to Sampson et al. (1995) (i.e. 10 min mean speed = 0.88 × 1 min mean speed).



- **Contents**

  Points of analysis:
  - Center position of tropical cyclone
  - Accuracy of center position determination
  - Direction and speed of movement
  - Central pressure
  - Maximum sustained wind speed (10-minute average)
  - Maximum wind gust speed
  - Radii of wind areas over 50 and 30 knots

  24-, 48- (45-) and 72- (69-) hour forecasts:
  - Center position and radius of probability circle****
  - Direction and speed of movement
  - Central pressure
  - Maximum sustained wind speed (10-minute average)
  - Maximum wind gust speed

  96- and 120- hour forecasts:
  - Center position and radius of probability circle****
  - Direction and speed of movement

**** A circular range into which a tropical cyclone is expected to move with a probability of 70% at each valid time.

Figure 5. Tropical cyclone information from the Regional Specialized Meteorological Center (RSMC) Tokyo/Japan Meteorological Agency (JMA) (http://www.jma.go.jp/jma/jma-eng/jma-center/rsmc-hp-pub-eg/RSMC_HP.htm).

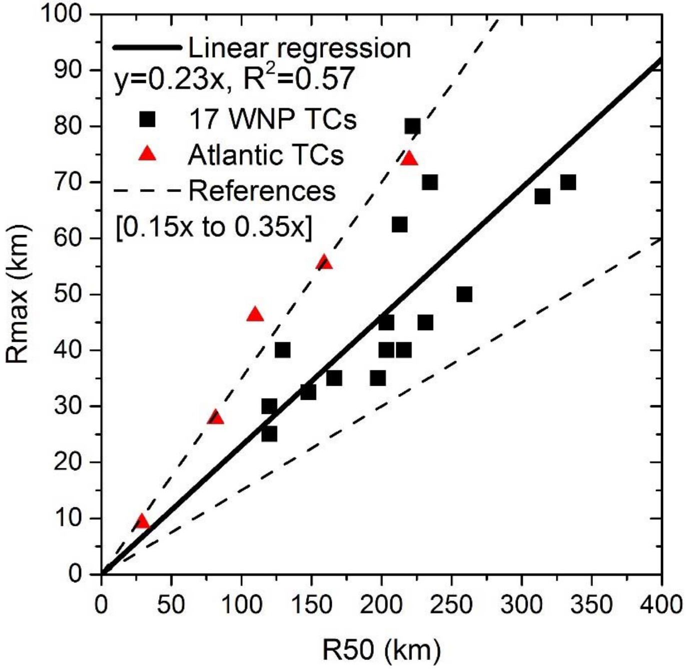


Figure 6. Relationship between the radius of the 50 kt winds around the typhoon (R_{50}) and the maximum wind radius (R_{max}). The two broken lines indicate the range in which 95 % of the plots fall (i.e. 95 % prediction interval). The Atlantic TC plot derived from Kimball et al. (2004).

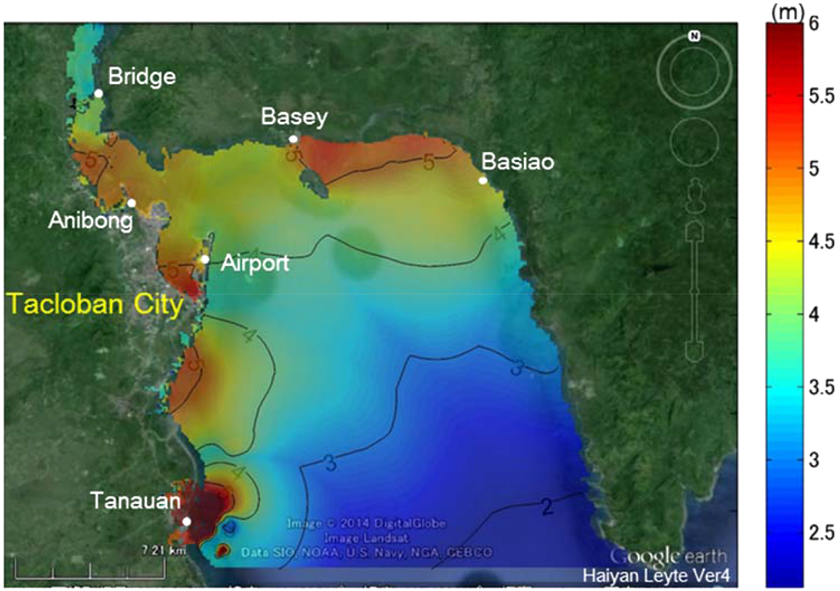


Figure 7. Maximum storm surge heights in San Pedro Bay due to the passage of Typhoon Haiyan (after Takagi et al., 2015a).

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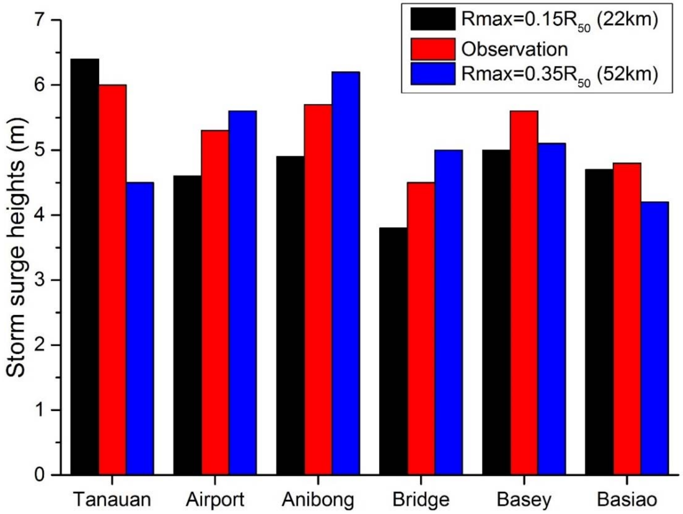

Figure 8. Simulated storm surge heights derived from different maximum wind radius (R_{max}) and observed heights.

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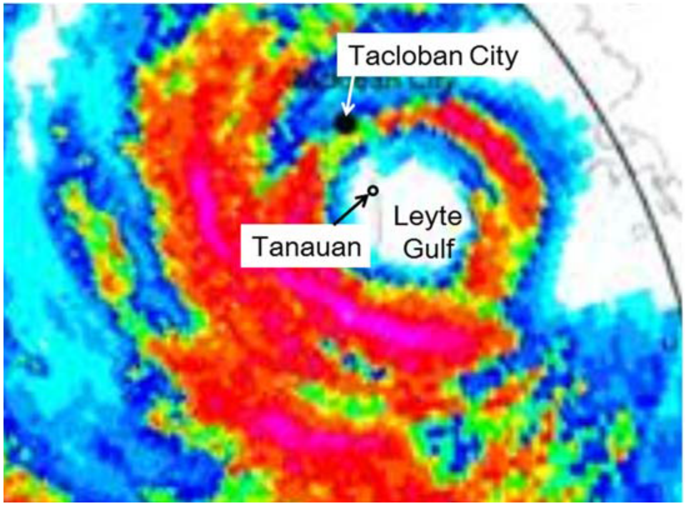

Figure 9. Rainfall intensity detected by the Doppler radar system in Cebu Island when the Typhoon Haiyan passed the Leyte Gulf.